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Energy security

Coping with multiple supply risks

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This study starts from the observation that today's Western trading nations are exposed to multiple risks of energy supplies, eg simultaneous shortage of oil and gas supplies. To cope with these risks, both oil and gas can be stockpiled. Adopting the viewpoint of a policy maker who aims at minimizing the expected cost of security of supply, optimal simultaneous adjustments of oil and gas stocks to exogenous changes such as an increase in the probability of supply disruption are derived. Against this benchmark, one-dimensional rules such as 'oil reserves for 90 days' turn out to be not only suboptimal but also to suggest adjustments exacerbating suboptimality.

Keywords: Security; Risk management; Supply risks

Today's national economies are becoming more interdependent at a rapid pace. At the same time, industrial countries, reacting to the oil crises of the 1970s, still aim at increasing the degree of their autarky in the energy domain. In particular, the International Energy Agency (IEA) has issued directives requiring member countries to hold oil reserves for 90 days' worth of national consumption (IEA [2]). These fuel-specific rules neglect the fact that economies rely on a multitude of resources simultaneously, many of which are supplied from abroad. Strategies for coping with simultaneous disruptions of several energy supplies do not seem to have attracted much attention so far, with the notable exception of Sanghvi *et al* [4] in the context of a specific linear programming application.

The objective of this contribution is to point out, for the most simple case of two risky energy supplies, some implications of general decision rules that focus on one energy supply only. For example, is it optimal to increase reserves of gas if the risk of a gas shortage is expected to increase, without any regard of the possible synergies between oil and gas reserves? Not too surprisingly, it turns out that decision rules focusing on a single risky supply not only are suboptimal at a given point of time but also run the considerable danger of inducing inappropriate adjustments.

The plan of the paper is as follows. First, a simple objective function for dealing with two risky energy supplies is developed. Next, decision rules for adjusting one supply to a changing environment are derived and contrasted to more globally optimal rules based on simultaneous adjustments in both of the energy sources considered. The last section offers a few conclusions.

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Table 1 Probabilities and losses caused by supply disruptions

Disruption of Oil	Gas	Probability	Loss
No	No	$(1 - p_O)(1 - p_G)$	0
Yes	No	$p_O(1 - p_G)$	L_O
No	Yes	$(1 - p_O)p_G$	L_G
Yes	Yes	$p_O p_G$	L_{OG}

Optimizing reserves: some basic considerations

This section is devoted to an optimization model that takes into account multiple risks for oil and gas, abstracting from other energy sources as well as non-energy factors of production. It is appropriate to state the simplifications that will be formally introduced later. (i) The objective is to minimize the sum of the costs of prevention and the one-period expected GDP loss in case of a supply disruption (see Mork and Hall [3] for an estimate of GDP loss in the case of the USA). In Table 1 all possible outcomes a national economy is facing are listed including the related probabilities and losses, assuming uncorrelatedness of risks. (ii) The interruption shall be normalized to last one year.

The GDP loss of an oil supply disruption L_O can be lowered by an increase in stocks S_O , with decreasing returns at the margin:

$$L_O = L_O(S_O) \quad \text{with} \quad \frac{\partial L_O}{\partial S_O} < 0$$

$$\text{and} \quad \frac{\partial^2 L_O}{\partial S_O^2} > 0 \quad (1)$$

where S_O are stocks of oil, without distinguishing the stage of refining.

A gas supply disruption will cause losses L_G , which can be lowered by a stockpiling of gas:

$$L_G = L_G(S_G) \quad \text{with} \quad \frac{\partial L_G}{\partial S_G} < 0$$

$$\text{and} \quad \frac{\partial^2 L_G}{\partial S_G^2} > 0 \quad (2)$$

where S_G are stocks of gas.

Losses in terms of GDP will of course be maximum if oil and gas are disrupted simultaneously (L_{OG}). They can also be reduced:

$$L_{OG} = L_{OG}(S_G, S_O)$$

with

$$\frac{L_{OG}}{\partial S_G} < 0, \quad \frac{\partial L_{OG}}{\partial S_O} < 0,$$

$$\frac{\partial^2 L_{OG}}{\partial S_G^2} > 0, \quad \frac{\partial^2 L_{OG}}{\partial S_O^2} > 0 \quad (3)$$

The decision problem of the policy maker can be seen as minimizing total expected cost due to preventive effort and expected loss, the two decision variables being S_O (stocks of oil) and S_G (stocks of gas). By increasing S_G and/or S_O , the policy maker can reduce the expected GDP loss in case of a supply shortage. However, by doing this, he would also run into some other costs with certainty because holding stocks uses space and capital. For simplicity, marginal costs (π_O and π_G , respectively) are assumed independent of S_O and S_G .

In formal terms, the objective function reads

$$\min Z = p_O(1 - p_G)L_O + (1 - p_O)p_G L_G$$

$$+ p_O p_G L_{OG} + \pi_O S_O + \pi_G S_G \quad (4)$$

where

π_O = marginal cost of oil stocks (assumed constant)

π_G = marginal cost of gas stocks (assumed constant)

First, it must be admitted that this objective function is much more normative than descriptive of actual behavior of policy makers. Indeed, the objectives of energy policy do not appear too well-defined (for a discussion of the US case, see Smith [5]). Second, it should be noted that there are many more ways to influence the security of energy supplies than just through S_G and S_O . Insulation of homes is considered to be a major means for decreasing dependence on imported oil in the USA. On the other hand, rationing remains a popular measure for dealing with unexpected shortages. Thus, the choice of decision variables is much wider than suggested by Equation (4). However, in what follows we shall focus on S_O and S_G because they are of decisive importance for longer run options of energy policy in all Western countries.

As a first step, necessary conditions for an interior optimum are derived, yielding

$$\frac{\partial Z}{\partial S_G} = (1 - p_O)p_G \frac{\partial L_G}{\partial S_G}$$

$$+ p_O p_G \frac{\partial L_{OG}}{\partial S_G} + \pi_G = 0 \quad (5)$$

With regard to oil shocks, we obtain

$$\frac{\partial Z}{\partial S_O} = p_O(1 - p_G) \frac{\partial L_O}{\partial S_O} + p_O p_G \frac{\partial L_{OG}}{\partial S_O} + \pi_O = 0 \quad (6)$$

It should be noted that optimal values S_G^* , S_O^* do not themselves appear in the two equations. However, as soon as gradients are fixed optimally at $(\partial L_G / \partial S_G)^*$ and $(\partial L_O / \partial S_O)^*$, corresponding optimal values S_G^* and S_O^* are determined through Equations (1) and (2). Specifically, solving Equation (5) for $(\partial L_G / \partial S_G)$, we obtain

$$\frac{\partial L_G}{\partial S_G}[S_G^*] = - \frac{p_O p_G \frac{\partial L_{OG}}{\partial S_G} + \pi_G}{(1 - p_O) p_G} < 0$$

as long as

$$\pi_G > p_O p_G \left| \frac{\partial L_{OG}}{\partial S_G} \right| \quad (7)$$

The inequality condition could conceivably be violated, implying that stocks are too large for mitigating GDP losses due to a gas shortage anymore. For this to happen, the expected marginal value of a GDP loss caused by the simultaneous shortfall of gas and oil supply would have to exceed the marginal cost of holding gas reserves. However, since this combined event has a small probability of occurrence, the RHS of the inequality in Equation (7) is small, causing it to be satisfied as a rule. In the initial optimum, there would therefore still be an interest in increasing the size of gas stocks.

For oil, an analogous derivation yields

$$\frac{\partial L_O}{\partial S_O}[S_O^*] = - \frac{p_O p_G \frac{\partial L_{OG}}{\partial S_O} + \pi_O}{p_O(1 - p_G)} < 0$$

as long as

$$\pi_O > p_O p_G \left| \frac{\partial L_{OG}}{\partial S_O} \right| \quad (8)$$

Because of the symmetry of Equations (7) and (8), the same conclusions can be drawn about the optimal size of oil stocks.

Pitfalls on one-dimensional decision rules

Policy making both at the national and at the international level (in particular, as suggested by IEA)

tends to focus on one supply risk at a time, resulting in what may be dubbed one-dimensional decision rules such as 'oil for 90 days'. In the following, this (too narrow) way of looking at the problem will be mimicked by holding constant the decision variable S_O and varying stocks of gas S_G . In these artificial 'optimal' conditions, how would the stocks of gas be adjusted?

For analyzing this issue in the framework of the model, let there be an increase in the likelihood of a disruption of gas supply. Therefore, Equation (7) can be used to determine how the dependent quantity $\partial L_G / \partial S_G$ would have to be adjusted when p_G increases. Partial differentiation of Equation (7) yields

$$\frac{\partial \left(\frac{\partial L_G}{\partial S_G} \right)}{\partial p_G} = \frac{\pi_G}{(1 - p_O) p_G^2} > 0 \rightarrow \frac{\partial S_G^*}{\partial p_G} > 0 \quad (9)$$

Due to the change impacting on the decision situation, the value of the gradient $\partial L_G / \partial S_G$ has to be set anew. According to Equation (9), it will move towards zero while remaining negative. This adjustment will call for an increase of stocks of gas (cf. the assumptions introduced in the context of Equation (2)). Adjusting gas stocks in the wake of an increased risk of disruption conforms with intuition; however, closer inspection of Equation (9) shows the amount of adjustment to depend positively on π_G . Thus, the higher the marginal cost of additional stock piling, the more one would be led to build reserves. This implication makes little sense, but serves to illustrate the risks inherent in pursuing a one-dimensional policy in the public interest.

Moreover, according to Equation (9) the strength of the reaction depends negatively on p_G , the probability of the shortfall of gas supply, another counter-intuitive implication that may again serve to emphasize the shortcomings of one-dimensional decision rules.

A more global analysis

After this criticism of the one-risk-at-one-time policy of industrial countries with regard to security of energy supply, we now turn to a more global approach by admitting of simultaneous adjustment of both gas and oil stocks. It will be shown that S_G and S_O must be set in a coordinated fashion. We consider again an increase in the likelihood of a disruption of gas supply as an exogenous shock calling for adjustment. Thus, the impulse is given by $dp_G > 0$.

This impulse impinges on first-order optimal conditions given in Equations (5) and (6), giving rise to adjustments dS_G^* and dS_O^* in the neighborhood of the initial optimum, with necessary conditions again satisfied at the new optimum. Accordingly, the total differential of Equation (5) must amount to zero:

$$\begin{aligned} (1-p_O)p_G \frac{\partial^2 L_G}{\partial S_G^2} dS_G^* + (1-p_O) \frac{\partial L_G}{\partial S_G} dp_G \\ + p_O p_G \frac{\partial^2 L_{OG}}{\partial S_G^2} dS_G^* + p_O p_G \frac{\partial^2 L_{OG}}{\partial S_G \partial S_O} dS_O^* \\ + p_O \frac{\partial L_{OG}}{\partial S_G} dp_G = 0 \end{aligned} \quad (10)$$

The impulse $dp_G > 0$ also serves to disturb the first-order optimum condition stated in Equation (6), resulting

$$\begin{aligned} p_O(1-p_G) \frac{\partial^2 L_O}{\partial S_O^2} dS_O^* - p_O \frac{\partial L_O}{\partial S_O} dp_G \\ + p_O p_G \frac{\partial^2 L_{OG}}{\partial S_O \partial S_G} dS_G^* + p_O p_G \frac{\partial^2 L_{OG}}{\partial S_O^2} dS_O^* \\ + p_O \frac{\partial L_{OG}}{\partial S_O} dp_G = 0 \end{aligned} \quad (11)$$

In matrix algebra, the two equations can be written as

$$\begin{bmatrix} (1-p_O)p_G \frac{\partial^2 L_G}{\partial S_G^2} + p_O p_G \frac{\partial^2 L_{OG}}{\partial S_G^2} & p_O p_G \frac{\partial^2 L_{OG}}{\partial S_O \partial S_G} \\ p_O p_G \frac{\partial^2 L_{OG}}{\partial S_O \partial S_G} & p_O(1-p_G) \frac{\partial^2 L_O}{\partial S_O^2} + p_O p_G \frac{\partial^2 L_{OG}}{\partial S_O^2} \end{bmatrix} \times \begin{bmatrix} dS_G^* \\ dS_O^* \end{bmatrix} = \begin{bmatrix} -(1-p_O) \frac{\partial L_G}{\partial S_G} - p_O \frac{\partial L_{OG}}{\partial S_G} \\ p_O \frac{\partial L_O}{\partial S_O} - p_O \frac{\partial L_{OG}}{\partial S_O} \end{bmatrix} dp_G \quad (12)$$

The solution of the resulting system of two simultaneous equations yields (with $\Delta > 0$ due to positive definiteness of the matrix on the LHS of Equation (13)):

$$\begin{aligned} \frac{dS_G^*}{dp_G} = \frac{1}{\Delta} & \left| \begin{array}{c} + \\ -(1-p_O) \frac{\partial L_G}{\partial S_G} - p_O \frac{\partial L_{OG}}{\partial S_G} \\ p_O \left(\frac{\partial L_O}{\partial S_O} - \frac{\partial L_{OG}}{\partial S_O} \right) \\ + \\ + / \ominus \\ p_O p_G \frac{\partial^2 L_{OG}}{\partial S_G \partial S_O} \\ p_O(1-p_G) \frac{\partial^2 L_O}{\partial S_O^2} + p_O p_G \frac{\partial^2 L_{OG}}{\partial S_O^2} \end{array} \right| \\ & + \\ & > 0 \quad \text{if} \quad \frac{\partial^2 L_{OG}}{\partial S_G \partial S_O} < 0 \end{aligned} \quad (13)$$

The positive sign of the lower off-diagonal element derives from the argument that additional oil stocks should be particularly helpful in the case of a severe 'combined loss' L_{OG} . Thus, if additional gas stocks also serve to strengthen the mitigating effect of oil reserves on the 'combined loss', the policy suggestion clearly is to adjust gas stocks upwards. Moreover, adjustment will in general be more marked if p_G takes on a high value. If only $\partial^2 L_O / \partial S_O^2$ and $\partial^2 L_{OG} / \partial S_O^2$ are of similar magnitude, the value of the determinant in the numerator of Equation (13) increases. In contrast to the preceding section, this result squares well with intuition.

However, if $\partial^2 L_{OG} / \partial S_G \partial S_O > 0$, the optimal adjustment can still remain positive as long as p_O is very small, ie as long as the other risk is negligible. Conversely $dS_G^* / dp_G < 0$ becomes a possible policy suggestion if p_O is very large and $\partial^2 L_{OG} / \partial S_G \partial S_O > 0$. This means that the stocks act as impediments to each other rather than synergetically at the margin.

As a final issue, should there optimally be an 'indirect' reaction to an increase in the riskiness of gas supplies through an increased oil stockage?

$$\begin{aligned} \frac{dS_O^*}{dp_G} = \frac{1}{\Delta} & \left| \begin{array}{c} + \\ (1-p_O)p_G \frac{\partial^2 L_G}{\partial S_G^2} + p_O p_G \frac{\partial^2 L_{OG}}{\partial S_G^2} \\ p_O p_G \frac{\partial^2 L_{OG}}{\partial S_O \partial S_G} \\ + / \ominus \\ + \end{array} \right| \end{aligned}$$

$$\begin{aligned}
& \left. \begin{aligned} & -(1 - p_o) \frac{\partial L_G}{\partial S_G} - p_o \frac{\partial L_{OG}}{\partial S_G} \\ & p_o \left(\frac{\partial L_O}{\partial S_O} - \frac{\partial L_{OG}}{\partial S_O} \right) \end{aligned} \right| \quad (14) \\
& + \\
& > 0 \quad \text{if} \quad \frac{\partial^2 L_{OG}}{\partial S_O \partial S_G} < 0
\end{aligned}$$

The optimal 'cross adjustment' of stocks to increased risk is indeed positive as long as stepping up both oil and gas reserves has a synergetic effect.

Final comments and conclusions

Aiming at autarky and fostering international exchange do not go well together. In energy, too, there is a trade off between the security of supply on the one hand and the cost of stockpiling (imported) energy on the other. With both national policies and recommendations by the International Energy Agency ('oil reserves for 90 days') focusing on one supply risk at a time, this trade off is unlikely to be the least-cost alternative. The problem is that it discards the very real possibility of a simultaneous shortfall of two or more energy supplies. In this contribution, the seemingly optimal reactions of a decision maker pursuing such a one-dimensional

policy to exogenous changes are derived. Not only can these adjustments go in the direction opposite to that derived from a more global optimization, but the suggested amount of adjustment clearly is non-optimal in any case. These findings point to the necessity of redirecting energy security policy away from addressing one source of energy at a time towards an approach capable of dealing with simultaneous supply risks and their specific properties.

References

- 1 Balas, Egon *The Strategic Petroleum Reserve: How Large Should It Be?* Report No 436, Carnegie Mellon University, Pittsburgh (1979)
- 2 International Energy Agency (IEA) Agreement concerning a International Energy Program OECD, Paris (1974)
- 3 Mork, KA and Hall, RE 'Macroeconomics analysis of energy price shocks and offsetting policies: an integrated approach' in Morek, KA (ed) *Energy Prices, Inflation, and Economic Activity* Ballinger, Cambridge, MA (1981)
- 4 Sanghvi, AP, Shavel, IH and Wagner, MH 'Fuel diversification, stockpiling, and system interconnection strategies for minimizing power system vulnerability to energy shortages' in Lev, B (ed) *Energy Models and Studies* North-Holland, Amsterdam (1983)
- 5 Smith, TR 'US energy policy in a changing market environment' *Economic Review Federal Reserve Bank of Kansas City* 1986 September/October 16-30